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Discharge Coefficient of 3-in-1 Hole with Various Inclination Angle and Hole Pitch

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Abstract

Discharge coefficients of 3-in-1 hole of three inclination angles and three spacing between holes are presented which described the discharge behavior of a row of holes. The inlet and outlet of the 3-in-1 hole both have a 15° lateral expansion. The flow conditions considered are mainstream turbulence intensities and density ratios of secondary flow to mainstream. The momentum flux ratios varied in the range from 1 to 4. The comparison is made of the discharge coefficients of three shaped holes to find an optimal hole with low flow loss. The results show that the discharge coefficients of 3-in-1 hole are highest in three shaped holes and therefore this article is focused on the measurements of discharge coefficients of 3-in-1 hole for various geometries and aerodynamic parameters. The measured results of 3-in-1 hole indicate that turbulence intensities, density ratios and momentum flux ratios have weak influence on discharge coefficients for inclination angle of 20°. The high turbulence intensity yields the small discharge coefficients for inclination angle of 45° and 90°. The increased both momentum flux ratios and density ratios lead to the increased discharge coefficients for inclination angle of 45° and 90°. The increased inclination angle causes the rapidly increased discharge coefficients. There is a weak dependence of discharge coefficients on hole pitches.

Keywords: aerospace propulsion system; gas turbine; film cooling hole; discharge coefficient

1 Introduction

Increasing the life of gas turbine blades can be achieved by cooling the blade effectively. Typically, this cooling process involves film cooling of blade surface. The present research about film cooling is focused on the improvement of film cooling effectiveness and the reduction of the coolant simultaneously. Film cooling holes with a diffuser-shaped expansion at the exit portion of the hole are believed to improve the film cooling performance on a gas turbine blade[1-5], so attention has been given to contouring the hole geometry recently.

Discharge coefficient is a very representative parameter in studying film cooling characteristics. The exact discharge coefficients are significant for detailed design of turbine blade. Gritsch, et al.[6-8] carried out experiment to investigate the influence of inclination angles, orientation angles and Mach numbers of internal and external crossflow on discharge coefficients. Bunker, et al.[9] studied the effect of relative location of turbulator and hole in a turbulated passage on discharge coefficients. Burd, et al.[10] measured discharge coefficients of film cooling hole for various length-to-diameter of film hole. Ethridge, et al.[11] investigated the effect of density ratio on film cooling performance on an airfoil with strong curvature and pressure gradient. Jones[12] carried out experiment and analysis of theory to validate simulating density ratios by using

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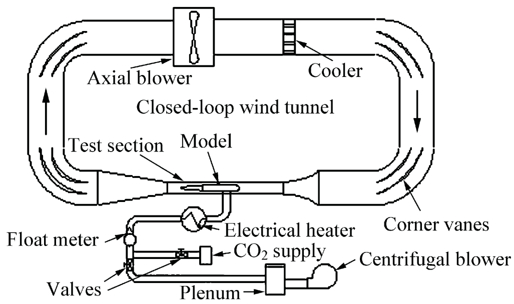
foreign gas. McGovern, et al. [13] and Walters, et al.[14] investigated film cooling characteristics by means of numerical simulation. Compared to a standard cylindrical hole, the increased cross-sectional area at the hole exit causes a reduction of the mean velocity and the increase of radial velocity, resulting in an increased cooling efficiency. The increased area at hole exit also yields the pressure recovery of coolant and therefore high discharge coefficient while the increased cross-sectional area at the hole inlet reduces the anti-kidney vortices at coolant coming in film hole. This effect is in favor of the decrease of flow loss at hole inlet.

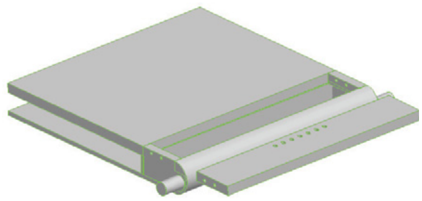
So far, no one has studied effect of mainstream turbulence intensity and spacing between holes on discharge coefficients. In this article, the comparison is made of the discharge coefficients of cylindrical hole, fanned hole and 3-in-1 hole, showing that the discharge behavior of 3-in-1 hole is highest in three shaped holes so that the measurement is focused on the discharge coefficients of 3-in-1 hole.

2 Experimental Test Facility

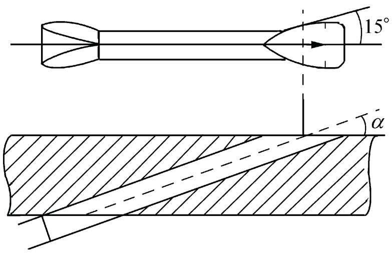
Measurements are conducted in a closed-loop wind tunnel with a secondary flow system for film cooling. The sizes of test section of this tunnel are 0.265 m high, 0.5 m wide and 2.2 m long. Fig.1(a) shows the sketch of the wind tunnel system. Fig.1(b) shows the test model. An interchangeable section with 7 film cooling holes is used to change the film hole model. The model consists of blunt body with a semi-cylinder leading edge of a diameter of 75.0 mm and two flat plates. The material of the test model is made of Plexiglas with a thickness of 22.5 mm. The ratio of thickness to diameter of film hole is 3.0. The ratios of length to diameter of film cooling hole increase with the decreased inclination angles. Fig.1(c) shows geometry of 3-in-1 hole. The 3-in-1 hole has 15° lateral expansion both at the inlet and outlet of the hole while the fanned hole only has an expansion at the hole outlet. The inlet expansion of film cooling hole is believed to significantly reduce the flow loss at hole inlet. The ratio of the width of inlet and outlet to diameter of 3-in-1 hole is 1.5.



(a) Sketch of the wind tunnel system



(b) Test model



(c) Geometry of 3-in-1 hole

Fig.1 Sketch of test apparatus.

The turbulence generated grid is located at 240 mm upstream of stagnation line of leading edge. The turbulence intensity is measured by hot wire. The mainstream in the tunnel is driven by an axial blower and the secondary flow is supplied by a centrifugal blower (air) or high pressure vessels (CO_2). The velocity of the mainstream is measured by using a Pitot tube probe. Free stream velocity is about 10 m/s and the responding local velocity of film cooling holes is about 13.9 m/s. The mass flux of secondary flow is measured by using a flow meter. The measurement certainty of discharge coefficient is about 4%.

3 Experimental Procedures

Momentum flux ratio is calculated by

$$I = \frac{\rho_c u_c^2}{\rho_\infty u_{loc}^2}$$

where ρ_c is the density of secondary flow, u_c the averaged velocity in cylindrical section of film hole, ρ_∞ the density of mainstream, and u_{loc} the local velocity of mainstream at the film hole exit.

Pressure coefficient is calculated by

$$C_p = 2(p - p_\infty^*) / \rho_\infty u_\infty^2$$

where p is local static pressure, p_∞^*, ρ_∞ and u_∞ are total pressure, density and velocity of the free stream, respectively.

The discharge coefficient C_D is the ratio of actual mass flow rate to ideal mass flow rate through the 7 film holes. The averaged C_D of 7 holes is calculated by

$$C_D = \frac{m_1}{m_2} = \frac{m_1}{(\pi d^2/4) \cdot 7\sqrt{2\rho_c(p_2^* - p_e)}}$$

where m_1 is the measured mass flow rate through the 7 holes, m_2 the ideal mass flow rate, d the hole diameter of the cylinder, p_2^* the static pressure measured in the plenum, which is used as the total pressure in the calculation of ideal mass flow rate due to the big enough size of the plenum, p_e is the static pressure of film hole exit.

The static pressure was measured by 15 taps placed on the side-walls of test channel as shown in Fig.2, the vertical distance from measurement surface of the model to the tap center is 1.5 mm. The corresponding pressure at the hole exit is used for the calculation of discharge coefficient. The configurations of test model are shown in Table 1 and the aerodynamic parameters are shown in Table 2.

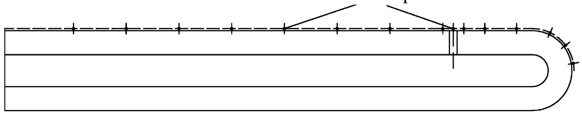


Fig.2 Distribution of pressure taps at side-wall of test channel.

Table 1 Geometry parameters of 3-in-1 hole

p/d	2	3	4
Inclination angle (α)/(°)	20	45	90

Table 2 Aerodynamic parameters of test

Momentum flux ratio (I)	1, 2, 4
Density ratio (DR)	1.0, 1.5
Turbulence intensity (Tu)/%	0.4, 8.0

4 Results and Discussions

Fig.3 shows the pressure coefficient distribution for various momentum flux ratios. It displays that the pressure coefficients decline quickly along flow direction at the curved surface region of leading edge and then increases slightly at the region where the semi-cylinder leading edge merges with the flat plate due to the existence of the separation bubble. Momentum flux ratios have weak influence on the pressure coefficients.

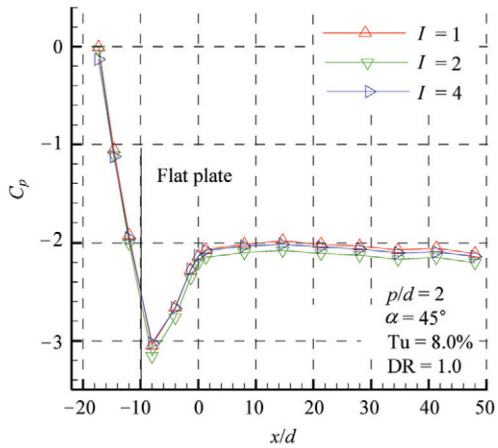


Fig.3 Distribution of pressure coefficient.

4.1 Effect of hole shape

Fig.4 presents the comparison of discharge coefficients of three shaped holes for the case of p/d = 3 and α = 45°, showing that the discharge coefficient of 3-in-1 hole is highest. This indicates that the increased cross-sectional areas, not only at hole outlet but also at hole inlet, are responsible for the increases of discharge coefficients. It is important to study systematically the discharge coefficient of 3-in-1 for designing turbine geometries. The static pressure at hole outlet and the cylindrical section area (the hole outlet area is larger than that of cylindrical section) are used for calculating ideal mass flow, possibly resulting in the discharge coefficients of fanned hole and 3-in-1 hole higher than 1.

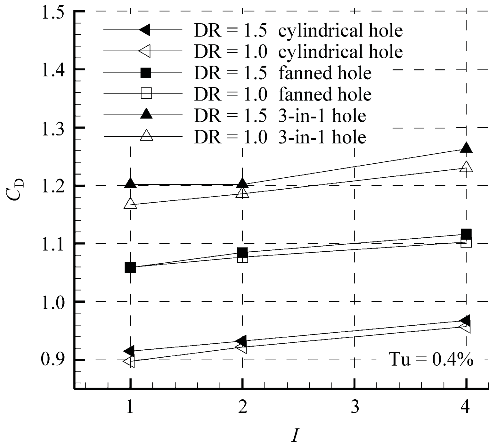
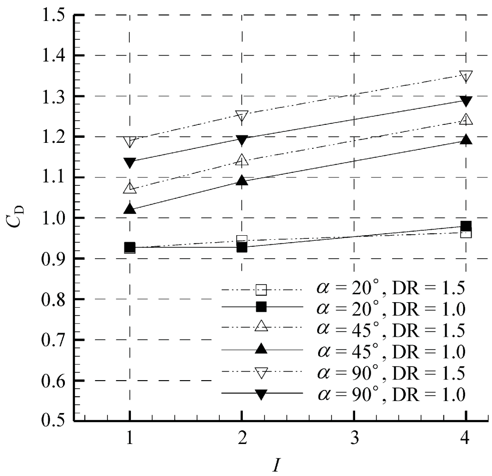


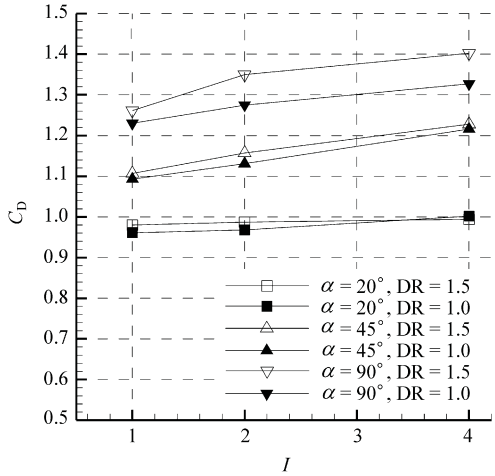
Fig.4 Effect of hole shape on discharge coefficient ($p/d = 3$, $\alpha = 45°$).

4.2 Effect of momentum flux ratio

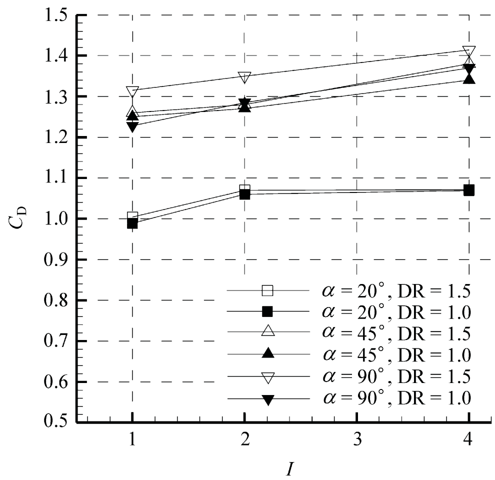
Fig.5 shows the effect of momentum flux ratios on discharge coefficients for the case of various hole pitches and turbulence intensities. For $\alpha = 20°$ and $p/d = 2$, there is a weak dependence of the discharge coefficients on the momentum flux ratios with a increase of about 0.03 when momentum flux ratio is raised from 1 to 4 (Fig.5(a)-5(b)). For $\alpha = 20°$ and $p/d = 4$, the discharge coefficients increase about 0.08 with the increased momentum flux ratio from 1 to 2 while there is a very weak variation when momentum flux ratio is raised from 2 to 4 (Fig.5(c)-5(d)). For $\alpha = 45°$ and $\alpha = 90°$, the increased momentum flux ratios from 1 to 4 yields the linear increased discharge coefficient (Fig.5(a)-5(d)). The effect of momentum flux ratio is significant compared to the case of $\alpha = 20°$. The increase of discharge coefficient with about 0.15 is found when



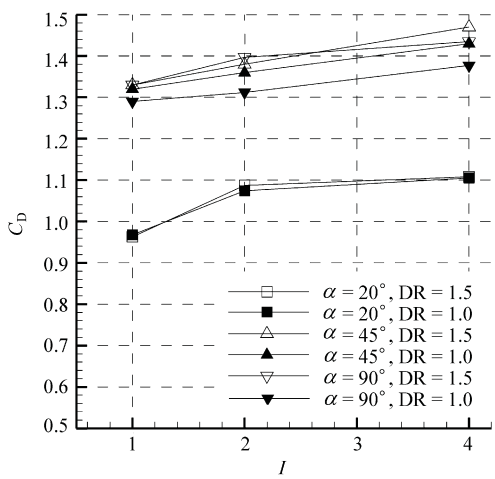
(a) $p/d = 2$, Tu = 8.0%



(b) $p/d = 2$, Tu = 0.4%



(c) $p/d = 4$, Tu = 8.0%



(d) $p/d = 4$, Tu = 0.4%

Fig.5 Distribution of discharge coefficient with various inclination angles and density ratios.

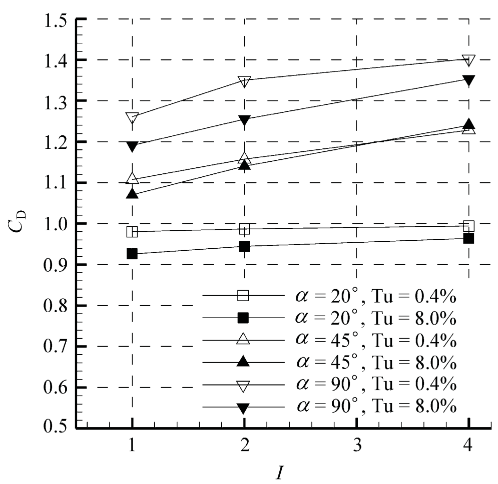
the momentum flux ratio is raised from 1 to 4. The increased momentum flux ratio produced relatively decreased flow loss at hole outlet and therefore higher discharge coefficient.

4.3 Effect of density ratio

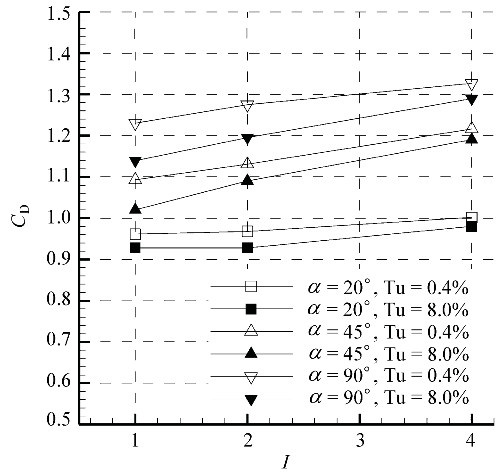
Fig.5 also shows the effect of density ratios on discharge coefficients. There is a very weak dependence of discharge coefficients on density ratios for the case of α= 20°. The effect of density ratios becomes significant increasingly with the increased inclination angles, especially for the case of p/d = 2. The high density ratios jet leads to the big discharge coefficient in the case of α= 45° and α= 90°. The most pronounced increase of discharge coefficient is about 0.07. Compared to air injection, the relatively low velocity of CO_2 injection causes the weak anti-kidney vortices at the film cooling hole inlet, resulting in the small flow loss and therefore the high discharge coefficients.

4.4 Effect of turbulence intensity

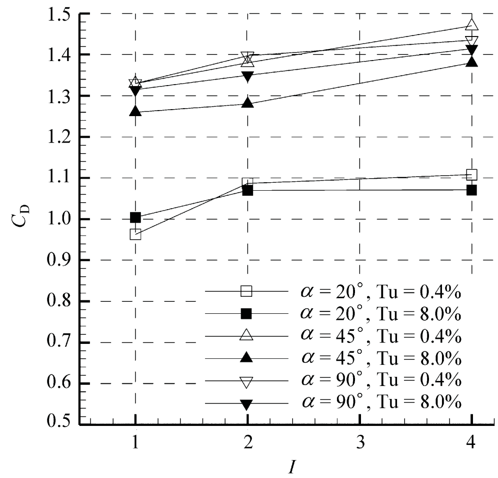
Fig.6 shows the comparison of discharge coefficients for different mainstream turbulence intensities. For α= 20° and p/d = 2, the increased turbulence intensity yields the decreased discharge coefficient while for α= 20° and p/d = 4, there is a very weak dependence of discharge coefficient on turbulence intensities. The effect of increased turbulence intensities is to reduce the discharge coefficients for the case of α= 45° and α= 90°, especially at the low momentum flux ratio. The most significant decrease of discharge coefficient is about 0.1. The high turbulence intensity produces the thin mainstream velocity boundary layer. The coolant mixes rapidly with gas of the high velocity after coming



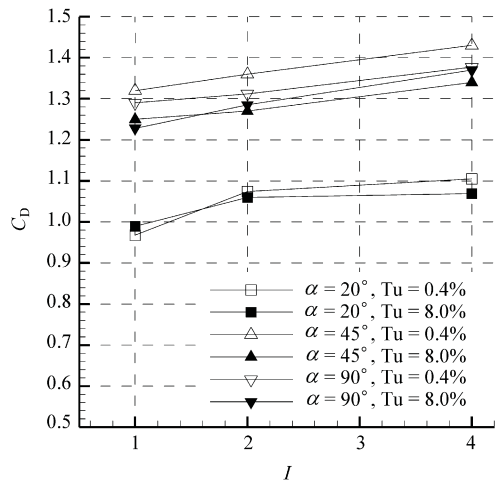
(a) p/d = 2, DR = 1.5



(b) p/d = 2, DR = 1.0



(c) p/d = 4, DR = 1.5



(d) p/d = 4, DR = 1.0

Fig.6 Effect of turbulence intensities and inclination angle on discharge coefficient.

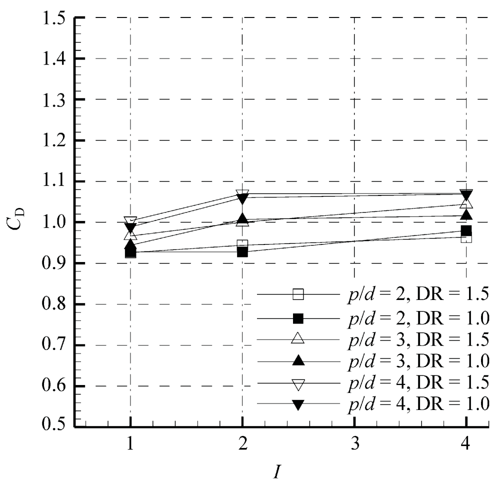
out of the exit of film cooling hole and therefore the lower discharge coefficients.

4.5 Effect of inclination angle

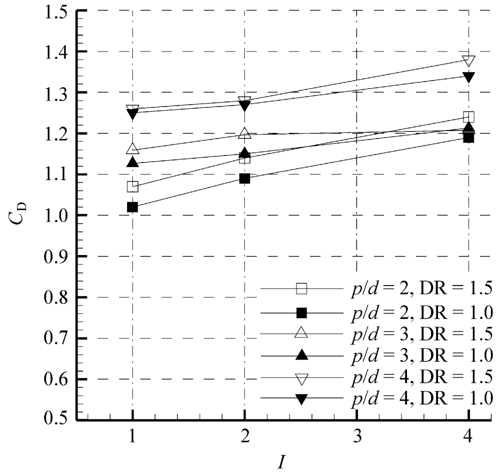
Fig.5 and Fig.6 also show the influence of inclination angles on discharge coefficients. For $p/d = 2$, a homogeneous increase of discharge coefficients with the increased inclination angles is found. For $p/d = 4$, there is a rapid lift of discharge coefficients when α raises from 20° to 45° while there is a relatively weak lift of discharge coefficients when α raises from 45° to 90°. The increase of discharge coefficient is from 0.3 to 0.5 when the inclination angle is raised from 20° to 90°. Firstly, some coolant has to go through a turn into the film cooling hole at the downstream side of the plenum. The inclination angle is bigger, the turn angle is smaller. The turn angle of $\alpha = 90°$ is 0°. The effect of turning is to increase the flow loss of hole inlet. Secondly, the ratios of hole length to diameter varies from 3.0 to 8.8 due to the decrease of inclination angle from 90° to 20°. The relatively long hole causes the heavy flow loss in the hole and therefore lower discharge coefficient.

4.6 Effect of hole pitch

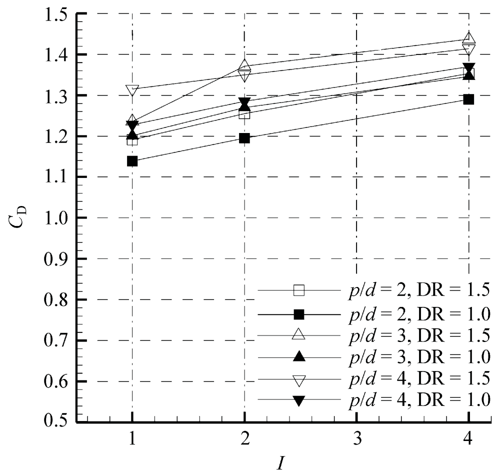
Fig.7 presents the effect of hole pitch on discharge coefficients. There is a relatively weak dependence of discharge coefficients on hole pitch compared to the influence of inclination angles. For Tu = 8.0%, the increased hole pitch causes the uniform rise of discharge coefficients. For Tu = 0.4%, the discharge coefficients of $p/d = 3$ is close to that of $p/d = 2$ while the discharge coefficients of $p/d = 4$ is higher. There are occurrence of not only mixing between jets and mainstream but also interaction of jets between neighboring holes for $p/d = 2$. However, the interaction of jets between neighboring holes is very weak due to the relatively long spacing between holes for $p/d = 4$. This effect indicates that the flow loss of hole exit for the case of $p/d = 2$ is large and therefore low discharge coefficients.



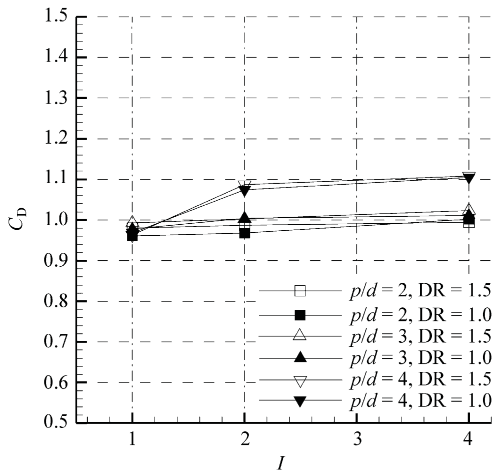
(a) $\alpha = 20°$, Tu = 8.0%



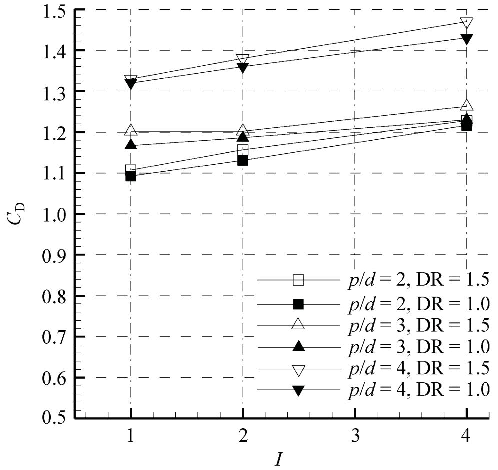
(b) $\alpha = 45°$, Tu = 8.0%



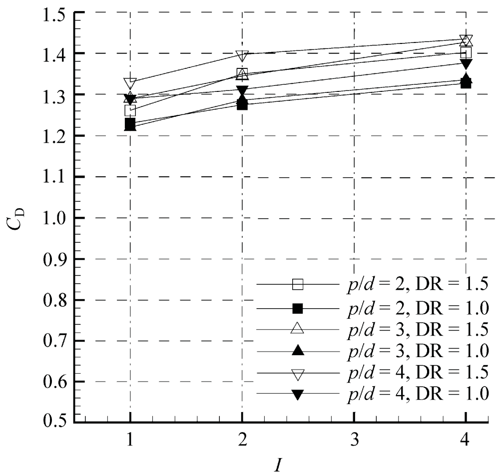
(c) $\alpha = 90°$, Tu = 8.0%



(d) $\alpha = 20°$, Tu = 0.4%



(e) α = 45°, Tu = 0.4%



(f) α = 90°, Tu = 0.4%

Fig.7 Effect of hole pitch on discharge coefficient.

5 Conclusions

The discharge coefficients of 3-in-1 hole for various film hole pitches and inclination angles are studied experimentally based on the comparison of discharge coefficients of various shaped holes. The mainly findings are following:

(1) The discharge coefficients of 3-in-1 hole are biggest in three shaped hole.

(2) Momentum flux ratios have weak influence on discharge coefficients for α= 20°. The increased momentum flux ratios lead to the increased discharge coefficients for inclination α= 45° and α= 90°.

(3) Density ratios have weak influence on discharge coefficients for α= 20°. The increased density ratios lead to the increased discharge coefficients for α= 45° and α= 90°.

(4) Turbulence intensities have weak influence on discharge coefficients for α= 20°. Higher discharge coefficients are measured in the condition of lower turbulence intensity for α= 45° and α= 90°.

(5) A pronounced augmentation of discharge coefficients with the variation of inclination angle from 20° to 90° is found.

(6) The slight increase of discharge coefficients with the increased hole pitches is observed.

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